Simulation Model of Gas Injection Aided Dewatering in Underground Mining

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ABSTRACT

A test model is presented for the simulation of dewatering by gas injection of a porous aquifer above longwall workings.

A finite difference model used in the oil industry was modified to match the underground mining conditions. The model is suitable to cope with the problem of dewatering reservoirs of low transmissivity. After comparing more versions, it has been concluded, that the investigated dewatering method can be proposed under special hydrogeological conditions only.

INTRODUCTION

New short-term dewatering technologies should be applied to protect mine work endangered by aquifers of small transmissivity. In many cases of aquifers in the roof of extractions a considerable volume of pore water cannot be discharged by using either some of the effective methods or the gravitational one because of the energy level decrease induced by dewatering.

Dewatering by compressed air is a technique that has been applied in civil engineering practice for a long time where underground workplaces are open in aquifers with special conditions. Experimental and semi-pilot operations were carried out in underground mining to extend the application of this method over larger field (5).

Considering the wide spread of the simulation methods for modelling physical phenomena, the preparation of a feasibility study by applying mathematical methods seemed to be useful.

The question was whether the well known compressed air technology could be used economically under the circumstances of Hungarian deep mining which are endangered by water inflows from roof-side aquifers. The widespread technique of oil production by gas or water injection is prepared for a given reservoir on the basis of mathematical modelling. This oil industry experience provided the basis for applying this programme to the conditions found in underground mining.

The question to be answered was: under what conditions can the dewatering method combined with gas injection be applied and made economical?

PRESENTATION OF THE MODEL

A short description of the special and unique solutions of the applied model is given below.

The governing equations of the model are the Darcy-law, the principle of the mass continuity and the equation of state for fluid systems. The applied differential equations are suitable to resolve any kind of isotherm problems in reservoir engineering. The number of phases, the dimensions of nodes and the boundary conditions can be specified arbitrarily.

GOVERNING EQUATIONS

The equations of a fluid system can be written as:

$$\Delta U_x + U_o + U_g + Q = C \cdot \frac{\partial p}{\partial t} \qquad (1)$$

where

U_x - intrinsic velocity of phase x (vol/time)
Q - intensity of source and/or sink (vol/time)
C - compressibility (vol/pressure)
p - pressure
t - time

The phase state at the end of the timestep is calculated by using the pressure distribution obtained from equation (1).

For fluid (x-phase)

$$\Delta\left(\frac{U_x}{B_x}\right) + Q_{xn} = \frac{\partial}{\partial t}\left(\emptyset \frac{S_x}{B_x}\right) \qquad (2)$$

For gas phase

$$\triangle\left(\frac{U_g}{B_g} + \frac{R_{sw} U_w}{B_w}\right) + Q_{gn} = - \frac{\partial}{\partial t}\left[\left(\frac{S_g}{B_g} + \frac{S_w \cdot R_{sw}}{B_w}\right) \varnothing\right] \quad (3)$$

expressions are valid, where

B_x, B_g - formation volume factor

R_{sw} - gas volume dissolved in fluid (water)

S_x, S_g - degree of saturation for water and gas

Q_{xn}, Q_{gn} - fluid and gas flow rate for nodes under normal conditions

O - porosity

The pressure of water phase is calculated implicity and the terms depending on the degree of saturation (as relative permeability, capillary pressure, etc) are determined explicitly (IMPES method). Significant stability and time step increment can be reached by the implicit calculation of the production from wells.

When discretising equation (1) the mass transport, the source and sink terms and the right-hand side can be handled separately from each other throughout the simulation procedure.

The flow filtrating through the interface of nodes within timestep t is calculated as follows:

$$Q_x = A_x /P_{rswz} - P_{eswl} + B_x/t \quad (4)$$

where $A_x = T \frac{k_r}{\mu}$

T - specific absolute transmissibility
k - relative hydraulic conductivity
μ - viscosity
B_x=f/P_{c1}S/ formation volume factor

P_c - initial capillary pressure of timestep
g - mean initial density of timestep (depth-dependent)

The flow rate in sink nodes (production wells) is computed by using the formation volume factor and the rate of dissolved gas content of the adjacent nodes. The source term (injection) depends on the PVP behaviour of the injected medium.

The volume change within the timestep is:

$$V = V \cdot C \cdot \Delta P \qquad (5)$$

where the compressibility C is phase and pressure dependent, therefore it can be calculated in an explicit way. The exponential functions of the fluid parameters and the changes of phases are also considered in the calculations.

The differential equation of the mass equilibrium of nodes is written as:

$$P_{rswz} \cdot \sum A_x - P_{rswz}\left[\sum A_x - \frac{V.C}{t}\right] = -Q - \frac{V.C}{t} \quad P_{rswl} - \qquad (6)$$
$$-\sum A_x \cdot B_x$$

where x is the phase of water and gas.

Dependent variables of the differential equations referring to the nodes covering the area to be modelled are the final pressures P_{rsw} of the timestep. Then the mass equilibrium equations are written for each phase and the degree of saturation is calculated by means of parameters PVT determined from pressure values.

SIMULATION PROGRAMME

The modified version of the numerical model presented above was used for the simulation of dewatering by gas injection. The programme code called EASY matches the requirements arising in the design and management of oil production for everyday. An error of less than 1 percent in the calculation of the mass equilibrium is reached by means of modified IMPES method. Full scale projects can be solved by computer IBM-PC, as a result of extensions determining the components of yield implicity and the timestep t automatically.

The evaluation of the results is simplified by the addition of postprocessor codes.

The following modifications of the programme used in the oil industry were applied to match the conditions of the given task.

- The water production at maximum depression is advantageous from the very beginning of dewatering. The calculation is fairly sensible in determining the timestep.

- The non-linearity induced by the relatively low water head is to be considered. The limits of saturation and pressure changes were restricted to 1%.

Initial input parameters required for running are as follows:

- geometric structure of the network
- pore volume, porosity
- relative depth
- specific, absolute hydraulic conductivity
- degree of gas saturation
- hydraulic pressure
- capillary pressure
- viscosity
- density
- formation volume factor.

Output list consists of data in tabulated form at the desired simulation time. These are:

- separated and total yields of the production and injection wells, the gas-water proportions.

- maps and profiles of isobars (water head) and degree of gas saturation,

- lists of pressure and saturation data for arbitrary slices and profiles of the network.

TASK TO BE SIMULATED

A simplified model of dewatering the porous aquifer in the roof of a longwall face was developed to illustrate the main features of the dewatering method based on compressed air injection. The filters are installed in the productive developments and the injection is carried on in the longitudinal axis of the strip.

The aquifer situated horizontally was covered by simulation grid of nodes of different size. A quarter with thickness of 15m consists of three slices. The total area (400m x 140m) is dewatered by means of 24 production wells. The initial water yield of the production well is assumed as $300m^3$/day, which decreases in a linear way as a function of the depression.

The parameters of basic variant are listed in Table 1. Several variants with some altered parameters and boundary conditions different from the basic variant were investigated and their results were compared with each other.

DISCUSSION AND COMPARISON OF VARIANTS

The main features of the different variants are listed below:

Variant No 1: Basic version. Inhomogeneous sandy aquifer. (Parameters in Table 1) Horizontal position. 5 production wells with total yield and 2 with half production are supposed over the simulated area (it is a quarter of the total area to be dewatered) (see Fig. 1). Water discharege without compressed air. Degree of gas saturation is 100%.

Variant No 2: Gas injection through four wells with a yield of 100 m^3/day each. The injection started on the 50th day of the dewatering operation. Fully saturated water.

Variant No 3: Inhomogeneous 3-layered strata (horizontal permeability values downwards from above are: 1, 10, 100 mD). The ratio between the vertical permeability values is the same. Fully saturated water.

Variant No 4: Same as variant No 3 but the initial gas saturation of the water is specified as zero.

Variant No 5: Inclined aquifer with an angle of 20°. Closed boundary along three sides. Single layer with permeability of 100 mD. (See Fig. 2) 5 production wells without gas injection.

Variant No 6: Same as variant No 5 but compressed air injection through 2 wells at the upper symmetrical axis.

The displayed and printed maps of the results of the different variants show the trends of the simulated processes. The simulation of the aquifer with fully gas saturated water (variant 1 and 2) hides the differences between the dewatering gravity and production completed by gas injection. The version with zero degree of saturation is more suitable for comparison.

Comparing the variants the following conclusions can be drawn:

- Some increment of water production occur when gas injection is applied. The rate of increment is 5% less when compared to the gravitational method. (Comparable variants: 1-2 and 5-6) (See Fig. 3)

- The areal distribution maps of gas saturation curves prove, that the injected gas "escapes" at the upper part of the horizontal layer and the compressed air is exhausted in the water production wells.

  Although gas-front can be recognised in the lower slice of the inhomogeneous multilayered system, a permanent water yield increase cannot be reached. (Variant No 3) (See Fig. 4).

- The vertical distribution of gas saturation is better in case of version 4, where the gas front spreads towards the production wells more slowly.

- The comparison of the pressure-time diagrams of variants 3 and 4 illustrates the differences of the reaction of the system to gas-injection. The pressure-stabilizing effect of the gas released by the pressure increase is higher than the pressure increment induced by the gas injection. Therefore no significant change can be seen on the pressure curve of the regular node 1,1 from the 50th day of production. The pressure change curve of the sink node (production well) shows gas exhaust phenomena. The water not saturated with gas is less compressibile at the given low pressures and the start in injection occurs significantly in the nodes near the gas injection well. (See Fig 5)

As a result of simulation of variant 1-4, one can conclude that dewatering by gas injection has not proved to be an effective technology in case of special stratigraphy of horizontal layers. The injected gas is exhausted towards the production well in the upper part of the aquifers to be dewatered.

The phenomenon takes place because under low pressure conditions the parameters for the water and gas components are different in order of magnitude. This phenomenon is proved by the experience according to which the compressed air outburst in the water production well is not caused by the unproper realization of the technology, but it can be derived from basic physical principles.

On the basis of the mentioned consideration an inclined part of the aquifer without water recharge was investigated (variant No 5). Gas injection at the top of the layer increased the velocity of dewatering, however characteristic yield increment did not occur. These boundary conditions are most similar to the problems of hydrocarbon reservoirs. In the Hungarian coal mining practice, however, special geological conditions like this exist very rarely. Moreover, the detection of the rechargeless tectonic blocks requires more expensive exploration to make decision on the proper dewatering technology (i.e. with or without gas injection).

CONCLUSIONS

On the basis of the results of simulation modelling and on that of the experience gained, we can conclude that the applied numerical model is suitable for the simulation of dewatering by gas injection. The phenomena observed in the practice could be matched qualitatively by simulation, however, the model verification of the actual data measured on the site has not been carried out. One can see, that a model calibration to the observed data is a suitable tool for the pratical design tasks with acceptable accuracy. The application of dewatering by gas injection seems to be unnecessary even under advantageous hydrogeological conditions.

ACKNOWLEDGEMENTS

This project is supported by a Gran No 1580 of the National Founds for Science of Hungary.

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Table 1

Initial Parameters of Variant No 1

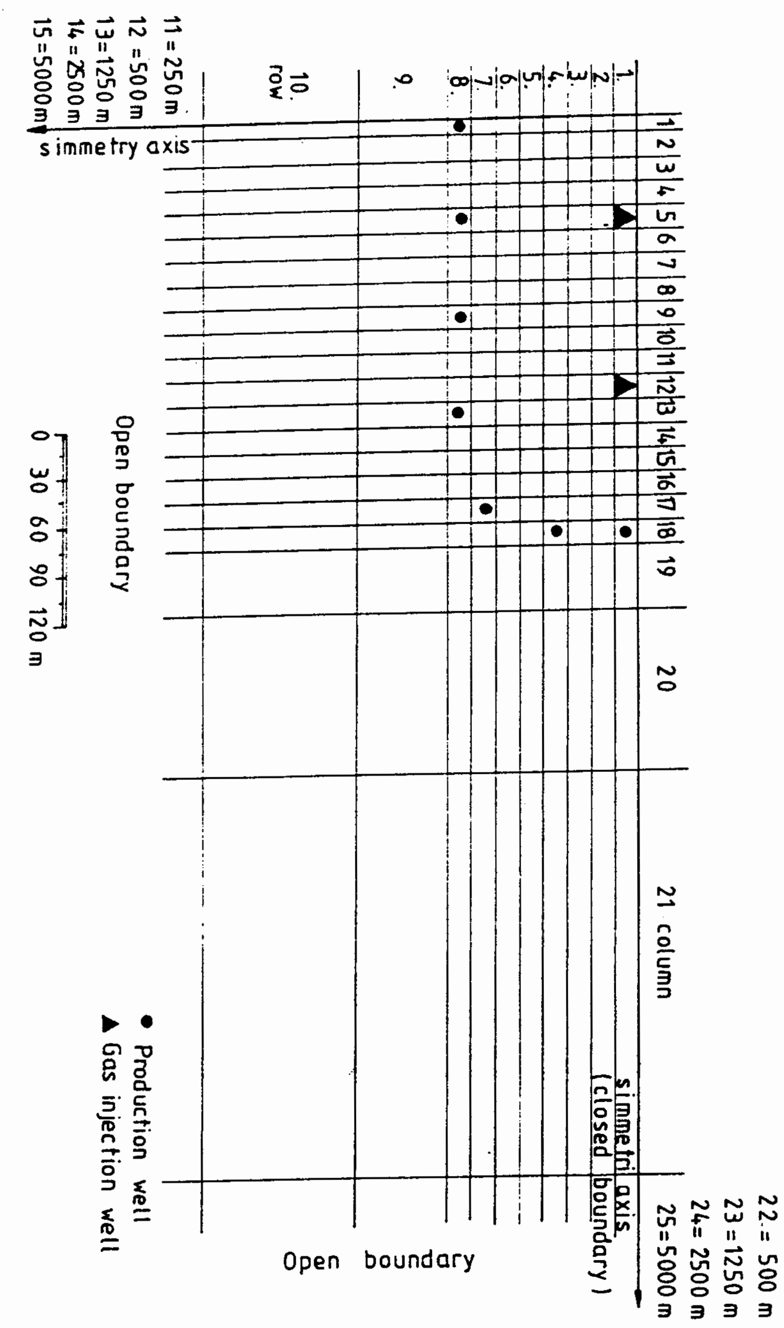
Simulated area: 10 x 10km
Size of network (being symetrical): 25 x 25 x 3 = 1125 nodes
Thickness of aquifer: 15m
Closed boundary at symetrical axes

Parameters of reservoir:

Porosity: 0,1
Permeability - horizontal: 100 mD
- vertical : 50 mD
Compressibility of rock : $6,8.10^{-5}$ 1/bar
Initial water head : 17 bar

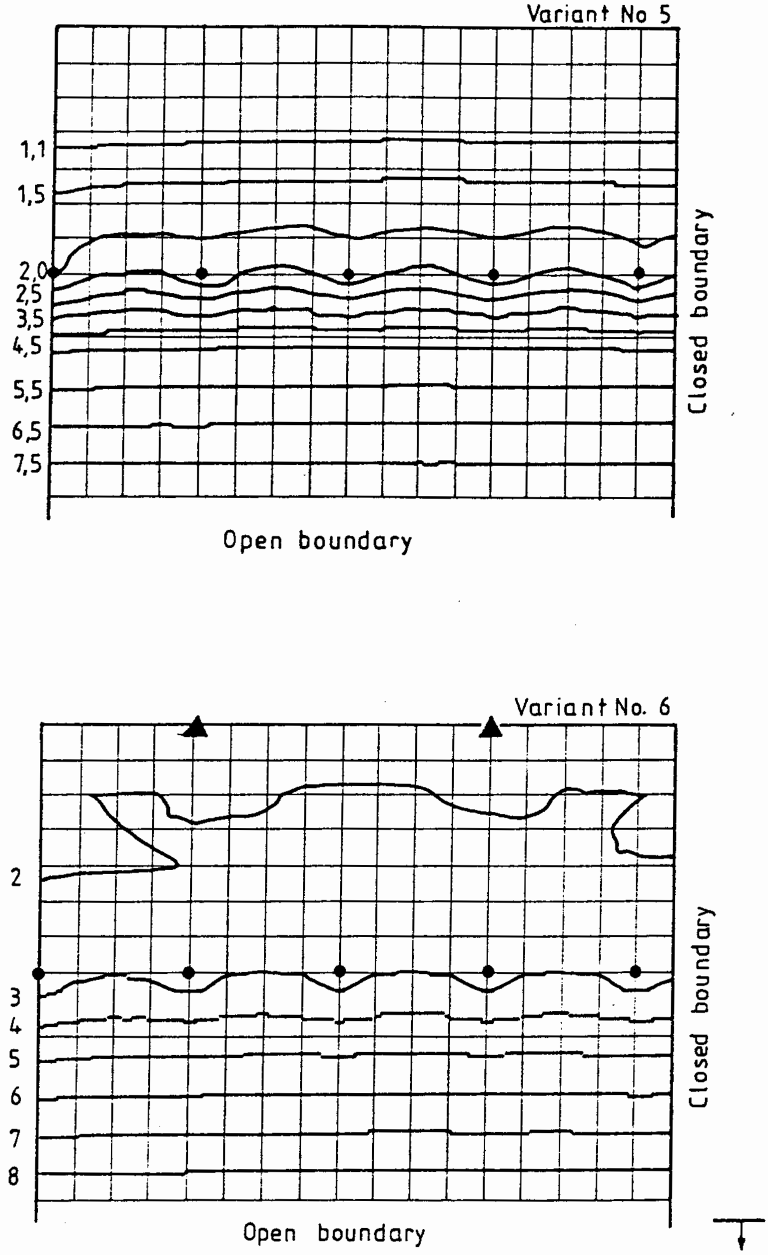
Parameters of phases

	Water	Gas
Normal density kg/m^3	1012,0	1,0155
Viscosity under pressure (cP)	0,95	0,0132
Formation volume factor (B_w)	$1,022-3,15.10^{-5}$xP	0,9693xP
Degree of gas saturation	0,0468xP	-



Schema of network for simulation

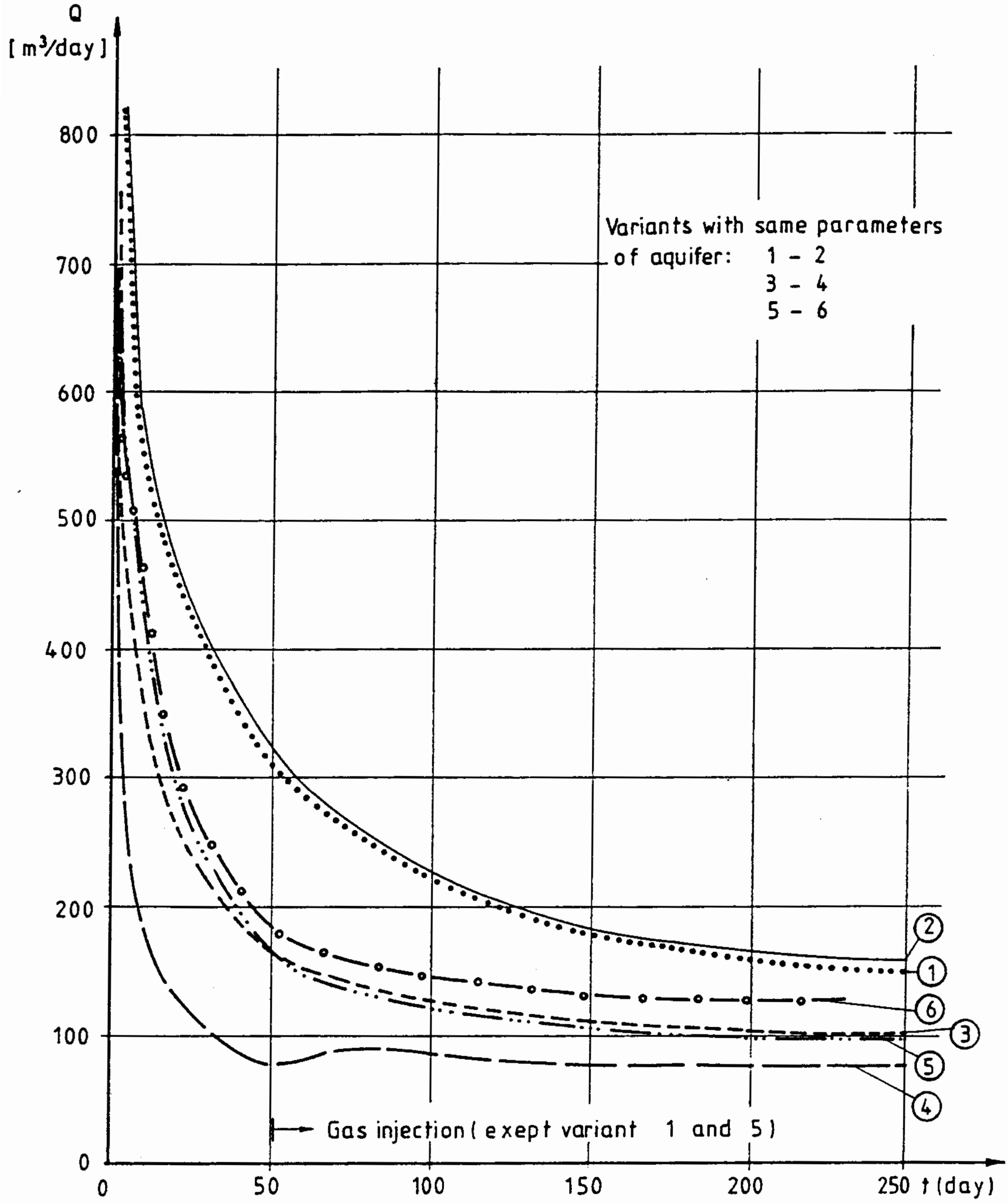
Fig. 1



● Production well
▲ Gas injection well

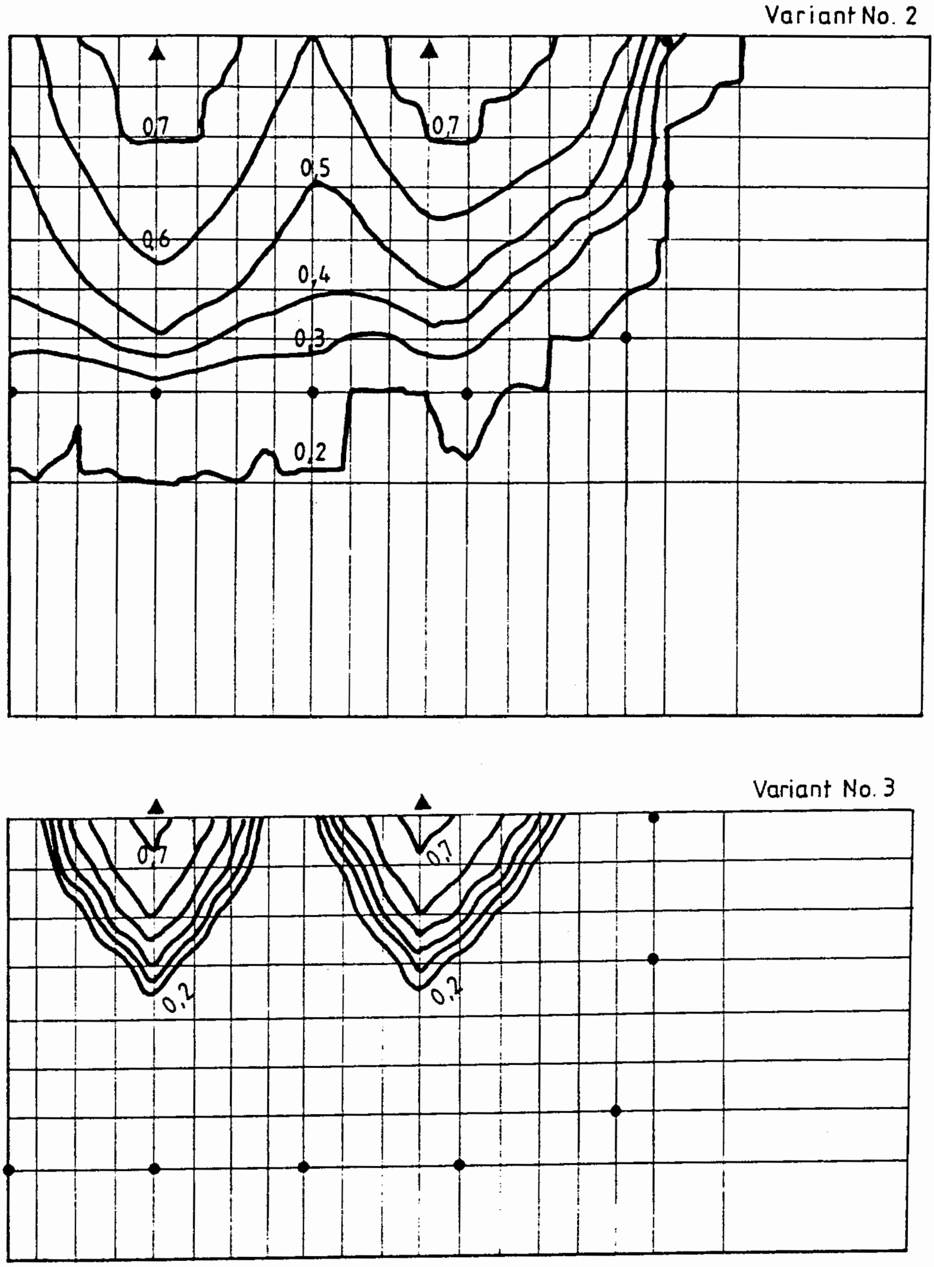
Water head maps of inclined variants at simulation time of 220 days [in bars]

Fig. 2



Change of water yield in different variants

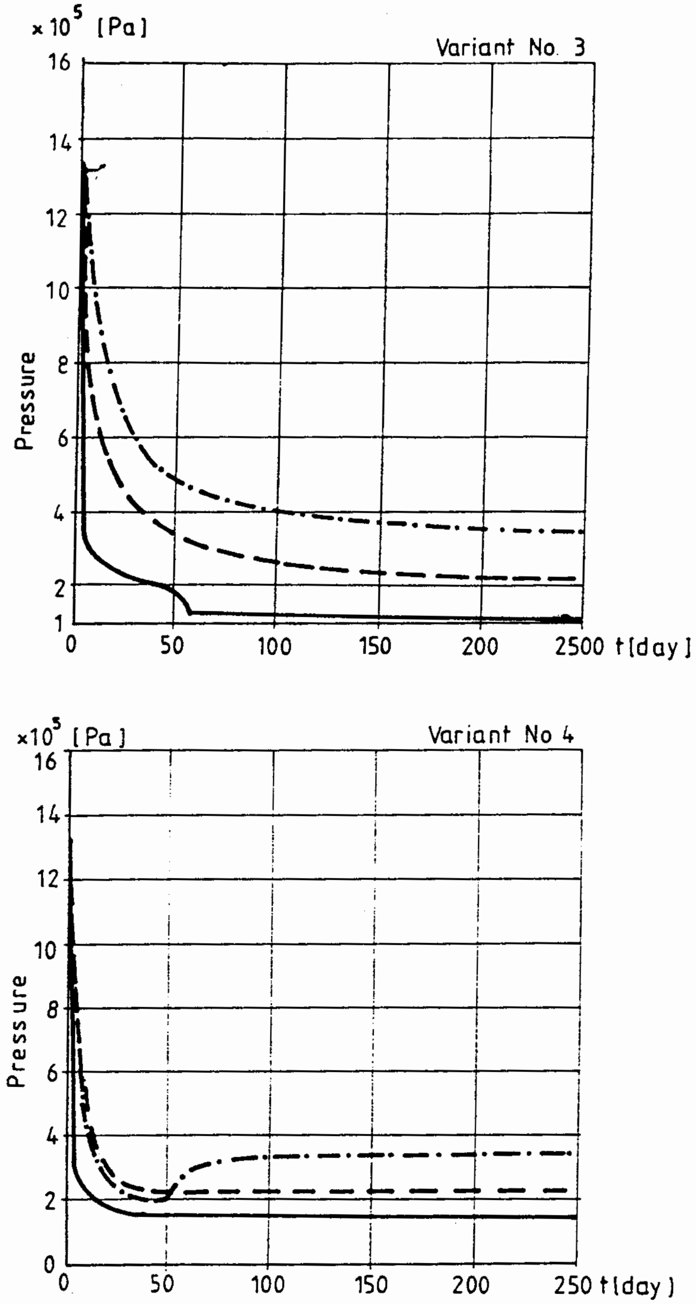
Fig. 3



● Production well
▲ Gas injection well

Degree of gas saturation of the upper slice after 200 days of gas injection

Fig. 4



——— Production well
– – – Regular node between injection and production wells
—·—· Regular node 1,1

Pressure in different nodes

Fig. 5.